Phase I Final Report

A New Magneto-Optic Based Flow Imaging Device
for Underwater Application

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SIGMA
SEATTLE DIVISION

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ABSTRACT

The Phase I research was intended to demonstrate the basic feasibility of constructing and optimizing a new magneto-optic 'sandwich' device intended for direct visualization of flaws in ferrous materials (steel) in a marine environment. The device is based on the property of some magneto-optic films to rotate the plane of polarization of an incident, linearly polarized light wave (Faraday magneto-optic effect). Such a device (in the 'sandwich' form) can be hand-held or operated by an automated submersible. Owing to the anticipated capability of such devices to observe the magnetic anomalies of flaws through considerable thickness of biofouling (up to 1/4 inch) this technique may not require clearing of surfaces before inspection. For these reasons, it should have considerable value as an inspection tool in a wide variety of marine environments, especially in floating offshore oil platforms and related inspection problems. The Phase I research demonstrated the feasibility of constructing magneto-optic based flaw imaging devices in a portable 'sandwich' design. Because these devices should be able to provide flaw images (in steel) directly, even through biofouling, the device is anticipated to have considerable commercial significance in marine inspection environments.

IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

Underwater inspection of steel structures would be greatly facilitated by the development of simple, portable, devices for the direct visualization of flaws in the presence of marine fouling. Devices for use by a diver or devices that could be part of an automated submersible, that could accomplish this task, would be a great benefit in many marine environments. This is especially the case for offshore oil platforms of all kinds and floating platforms in particular. But a versatile device of the type we propose would be useful in applications ranging from the inspection of ship hulls to drive shafts.

The investigation of ferrous materials by general electromagnetic methods has become a well established practice in materials research and in industry [1]. These methods can provide useful information about the tested object which includes the following:

    electrical conductivity σ
    magnetic permeability μ
    electric permitivity ε
    thickness
    discontinuities (flaws, voids, cracks, and inclusions)

Other parameters may be accurately inferred from this information including case hardening, cold work, heat treatment or annealing status. Unfortunately, most electromagnetic tests are not well suited for rapid inspection of large surfaces or structures, and do not usually produce flaw images directly. All electromagnetic techniques depend on some type of sensing device (pickup coils, Hall effect device, etc.) that responds to the electric, magnetic or electromagnetic field near the material specimen.

Often the sensing devices provide only crude indications of flaws, or require considerable data reduction before flaws can be fully characterized. It is proposed here that a new class of electromagnetic field sensing device, namely magnetic garnet films [2,3], be employed for the purpose of producing flaw images in ferrous materials and that this device be developed for the specific purpose of underwater inspection.

Bismuth doped garnet films are potentially very sensitive to weak magnetic fields. Garnet films have been designed and produced to have a switching field less than three gauss. This is the magnetic field that can switch the direction of magnetization in the entire film. Properly biased films up to four inches in diameter, or smaller portions thereof, can be switched in the presence of very weak magnetic fields, which, when added to the bias field, exceed the switching field. Owing to high potential sensitivity to weak magnetic fields (probably in the .01 gauss range) and to the demonstrated possibility of achieving high contrast magneto-optic visualization of the domain structure of the film [4], it is very likely that the weak magnetic fields associated with flaws in ferrous materials can be visualized using hand-held detectors of a design compatible with the needs of a human diver or an automated submersible.

The purpose of the proposed research is to fully explore this basic concept, using a new optical 'sandwich' design, and to demonstrate

feasibility by actually constructing a device capable of forming flaw images in ferrous materials. The new 'sandwich' design would consist of an electroluminescent panel (chemoluminescent panels may also be tried) and garnet films and various other planar optical elements in a stack. Such a device would be capable of forming images of flaws even in the presence of marine fouling at distances of, say, 1/4 inch. Because of the sandwich design (as opposed to a box as in Figure 1), problems with pressure compensation are eliminated. It would be applicable in areas currently investigated by devices employing magnetic particles in a watertight pouch. Unlike these techniques, direct instantaneous images of flaws would be available over large areas and at considerably high sensitivities using a far simpler hand-held device requiring very little support equipment. This new capability would provide a major new tool for inspection of underwater steel structures of any type, including ship hulls and especially offshore floating platform components. In the following, we outline the Phase I technical objectives, plans and tasks, and then provide a detailed account of the Phase I accomplishments. Sufficient background material is provided to understand the general approach (for both Phases I and II) to be taken in this work.

PHASE I TECHNICAL OBJECTIVES

The basic purpose of the proposed work is to demonstrate the feasibility of using currently available magneto-optic materials (magnetic garnet films) to produce direct visual images of flaws near the surface of ferrous materials. This is to be accomplished by using a compact hand-held 'sandwich' device involving electroluminescent and/or chemoluminescent lighting and a variety of other planar optical elements in a stack. This technological development would represent a major advance in existing marine inspection technology. Our principal objective will be to construct such a device and to perform feasibility tests on representative flaws in ferrous materials. In order to achieve this objective, we must be able to accomplish the following:

1. Demonstrate that a sandwich design involving an electroluminescent and/or chemoluminescent light source, polarizing materials, garnet films and partially reflecting optical surfaces can be made (and optimized) to produce high contrast images of flaws by imaging their associated magnetic flux leakage fields. Such a device will involve features of a pure reflection system which already exists (see Figures 1,2,3) and a transmission system (see Figure 4).

2. Demonstrate that the electric power requirements of such a device are modest and that, if necessary, it can be a completely self-contained (hand-held), battery-operated system. (Note that even if a chemoluminescent light source is used, the garnet film still must be biased by a current carrying coil surrounding the garnet film in order to achieve proper levels of sensitivity and erase prior images.)

3. Demonstrate that such a system is capable, in principle, of operating under the conditions of pressure and temperature commonly encountered in marine inspections.
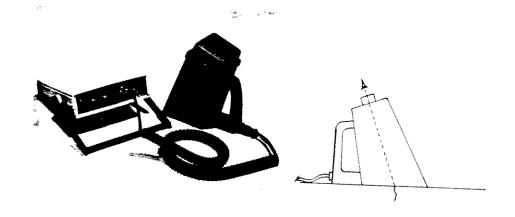
Figure 1. MI-201-A Flaw Visualization Instrument. This box design would be eliminated using a new design involving a sandwich of garnet films, electroluminescent panels, polarizing materials and various internally reflecting surfaces.
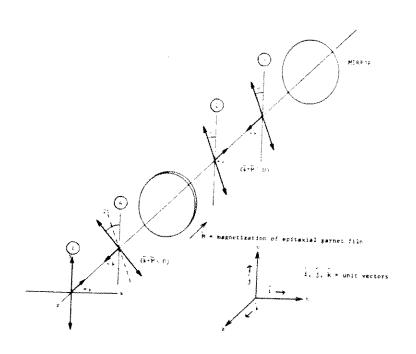
Figure 2. This figure illustrates the effect of a magneto-optically active garnet film on the plane of polarization of an incident light wave. (1) shows the incident light wave with wavevector $\bar{k} = |\bar{k}| \hat{k}$ along the negative z-axis and polarization along the y-axis. (2) shows a counter clockwise rotation of the plane of polarization due to passage of the light wave through the epitaxial garnet film. (3) shows the light wave (2) after reflection from a mirror and (4) shows the doubled Faraday rotation after the light wave of (3) passes back through the epitaxial film.

Polarized
Light

Analyzer

Epitaxial Magnetic
Garnet Film

Circular Coil Carrying Current I

Epitaxial Magnetic
Garnet Film

Fields inside and outside tend to lie
normal to the surface

Figure 3. Basic reflection mode geometry for near contact imaging devices employing magnetic garnet films. Note that most films are deposited on both sides of the substrate.

Light
Source

Polarizer

(Garnet Film)

Analyzer

$\bar{M}$

Figure 4. Basic elements of magneto-optic transmission mode display. The state of magnetization M in the garnet film is being observed.

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4. Demonstrate that the device can, in principle, withstand seawater corrosion effects (after appropriate sealing).

PHASE I WORK PLAN

In order to demonstrate the basic feasibility of producing flaw images in ferrous materials under conditions of water immersion at great depths (up to 1000 ft.), we will briefly review the available techniques 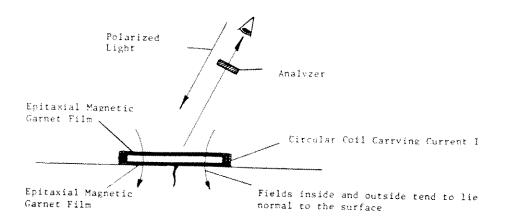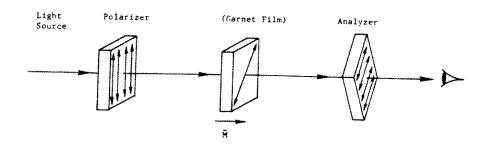for producing flaw images in ferrous materials using existing garnet film technology under less stringent conditions. General magneto-optic imaging principles and general methods for forming images using these films will be described. Once this background material has been presented, specific methods and tasks for achieving flaw images in ferrous materials using garnet film detectors in a sandwich design will be given.

General Magneto-Optic Displays

Bismuth substituted iron garnets [2-4] possess a large specific Faraday rotation θ_f which makes possible and practical both transmission and reflection mode magneto-optic displays of various types. A typical transmission mode display geometry is illustrated in Figure 4.

If linearly polarized light from the source(s) shown in Figure 3 is incident on a magnetic garnet film (magnetic material), the plane of polarization of the incident light will be rotated by an angle [4]

$$\theta \propto \theta_f \, k \cdot M \tag{1}$$

where θ_f is the specific Faraday rotation of the film, k is the wavevector of the incident light, and M is the local time dependent magnetization of the film at the point where the incident light passes through the film. The sign of the scalar product $k \cdot M$ determines the sense of the rotation. Note that in a solid, the Faraday rotation does not depend on the sign of the wavevector k, only on the angle between k and M. This means that the effect is doubled if a mirror or other reflective material is placed as shown in Figure 2. The mirror ensures that the beam will pass back through the epitaxial layer, thereby doubling the effective rotation of the plane of polarization.

The rotation of the plane of polarization of an incident, linearly polarized light beam serves as the basis of direct visualization methods. Ordinarily, in the absence of an applied field, domains (regions of uniform magnetization in the garnet film) are small. In many garnet films, especially those used in magnetic bubble memories, domains measure only several microns across [2]. However, in some garnet films the domains can be very large even when no biasing fields are present [3]. In still other materials, such as the material used in the commercially available devices, small applied fields (three gauss or less) can cause the domains to coalesce into a single large domain several inches across. Such large domains allow perturbations due to flaws to be visualized provided the film has a

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sufficiently large specific Faraday rotation achieved with Bismuth doping [4].

A Pure Reflection Mode Device

Owing to the requirements of near contact imaging (garnet film must be 'close' to the material otherwise anomalies are weakened with distance) and the need to reduce surface light reflections from the garnet film, a general reflection mode display geometry of the general type illustrated in Figures 2 and 3 can be used.

Note that the reflection mode of operation, depicted in Figures 2 and 3, has many desirable features. The Faraday rotation produced by reflection is just twice that which is produced by transmission (see Figure 2). Moreover, there are generally two magnetic garnet films on the substrate separated by a short distance (.02 inches typically). This increases the effective film thickness by a factor of two, and thus improves flaw image contrast.

The problem with such a design (in a marine environment) is that the light source is at some distance from the garnet film and this inevitably leads to a box-like imager as shown in Figure 1. Such a box must either be sturdy enough to withstand significant pressures (at 200 ft., 100 psi) or be filled with a clear liquid and fitted with a pressure balancing membrane to balance the seawater pressure against the pressure of the liquid in the container. Of course, a housing may have to be provided to protect the light source, etc.

Most of these difficulties could be eliminated by a new design which combines some of the features of a pure reflection design (Figures 2 and 3) and a pure transmission design (Figure 4). In this proposal we describe so-called 'sandwich' designs involving a garnet film and other optical elements which are 'backlighted' by an electroluminescent panel. Before describing this concept in detail, let us describe the state of the existing technology.

Ferrous Metals Inspection (An Existing Technology)

Spectron Development Laboratories (SDL) developed the first commercial magneto-optic based system for producing high resolution images of near-surface flaws in ferrous materials. This technology was purchased, further perfected and is now being marketed by Sigma [5-7]. The device (see Figure 1) employs a magnetic garnet film in an arrangement similar to that shown in Figure 3. In Figure 5, we illustrate a flaw image produced by the device using low frequency (60 Hz) time varying magnetic fields applied by a magnetic yoke. While this method of reflection imaging is successful for ferrous materials, under normal conditions, it is inadequate for imaging flaws in a marine environment where it would be desirable to rid the inspector of the box-type imagers.

The Sandwich Design

One concept for a sandwich design is illustrated in Figure 6. It is clear from this figure that the new sandwich design is a hybrid involving

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Figure 5. Image produced by the MI-201-A is a tight nonvisible crack in a steel bar (cross section 2 in. x 2 in.) possessing a long sinuous longitudinal crack. A 115 volt, 50 Hz yoke supplied an external low frequency excitation field B(t).

Analyzer

Front Surface Mirror (FSM)

Garnet Film 1
Substrate
Garnet Film 2

(FSM)

P

Electroluminescent Panel
(light source)
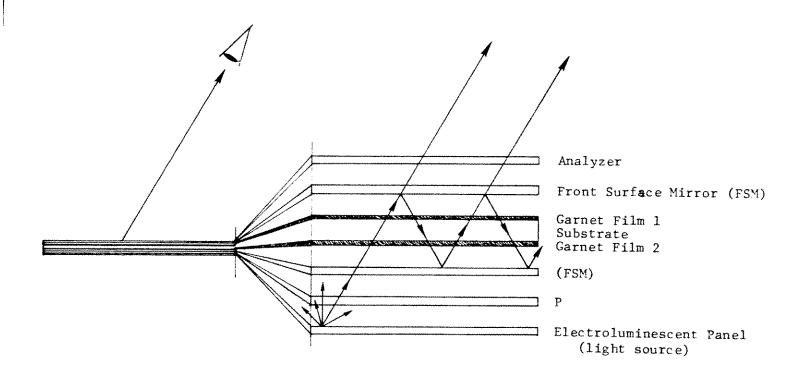
Figure 6. This design has two partially reflecting mirrors on either side of two epitaxial garnet layers. Note that light from the light source passes through a polarizer, then passes through the entire stack and reflects from the back of the mirror above the garnet films, back down through the garnet films and again reflects from the mirror below the garnet films. This happens a number of times and some of the light from the light source eventually leaks out of the stack reaching the viewer.

both transmission of light through the garnet film (one way) and multiple reflections through the film (analogous to the pure reflection mode of Figure 2). An electroluminescent panel is similar to a capacitor in that it consists of two conducting surfaces with a dielectric material between them. A luminescent pigment is dispersed within the dielectric material and, therefore, will be subjected to the electrostatic field of the charged capacitor. If an AC voltage is applied across the panel, the phosphor particles will be in a continuing state of excitation giving off a steady light in the form of a glow. For panel lighting applications, one plate or electrode of the panel is translucent to allow transmission of the light to the optical stack in this case.

Since the light phenomenon occurs by a means other than the temperature of the source, it fits the definition of luminescence. Since the source of excitation is an electric field, the panel is electroluminescent. The electroluminescent panel requires approximately 130 Vac at 400 to 1000 Hz for excitation. An inverter that operates from a 5 Vdc source is possible. Unless some method of compensation is provided, the light output of the electroluminescent panel will decrease with age. By incorporating the panel's capacitance as a part of the inverter circuit, the voltage and frequency output will be changed to properly compensate for the panel's aging and maintain an essentially constant light output. As mentioned earlier, we may also wish to consider chemoluminescent panels (liquid filled disks) instead of electroluminescent panels. The principle will be the same in either case.
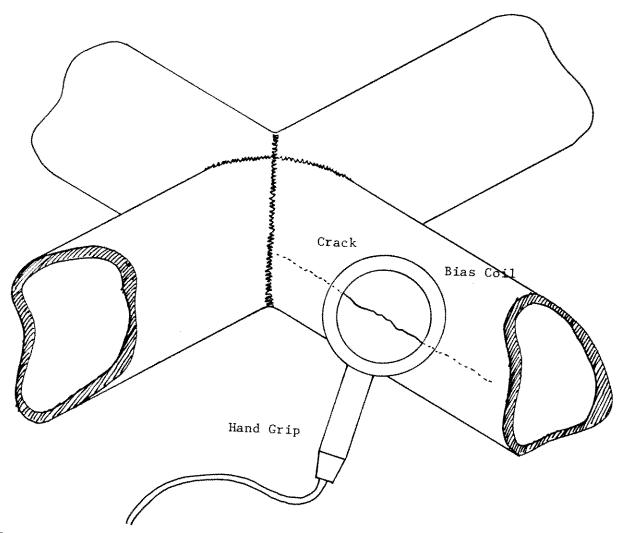
There are a number of unknowns involving the optimum optical configuration in any such design. The electroluminescent panel has a limited light output and this light must be used as efficiently as possible in forming a high contrast image of a flaw.

From Figure 6 it is clear that we have two partially reflecting surfaces (partially reflecting front surface mirrors in effect), a source of light (electroluminescent panel), the garnet film (two epitaxial layers on a nonmagnetic substrate) and two sheets of polarizing material. The most efficient design will be one that maximizes both the light intensity and the image contrast. These happen to be somewhat conflicting requirements since contrast is maximized by multiple internal reflections (in such a sandwich) while intensity depends on the amount of light which leaks out of the sandwich [8].

Our approach to realizing an optimum design will be both theoretical and experimental. We will calculate both the image intensity and contrast for a variety of designs involving different reflection coefficients, etc., and determine what ought to be an optimum arrangement. We will then construct such a system as shown in Figure 7. This system will be tested, refined and recommendations for hardening the system (making it portable and compatible with a marine environment) will be made.

Phase I Task Objectives

We suggest a phased approach aimed at the ultimate goal of systems designed for specific applications. Only the Phase I feasibility study will be detailed in this proposal. The objective of the Phase I study is to test

Figure 7. A highly schematic illustration of a hand-held version of the 'sandwich' imager is provided. A diver could use this device to image the flux leakage fields directly even through biofouling.

the basic feasibility of using a biasing coil, a magneto-optic garnet film, an external method of inducing fields in a test specimen, and magneto-optic imaging techniques involving electroluminescent panels and multiple internal reflections in a sandwich design to rapidly obtain images of discontinuities (flaws, inclusions, etc.) near the surface of two-dimensional ferrous materials that may have a considerable marine biofouling covering the flaw. The following five tasks will be performed under the Phase I program:

Task I - design a magneto-optic inspection system (Figures 6 and 7) incorporating an external source field and optical sandwich design.

Task 2 - procure the necessary magneto-optic garnet films, coils, support circuits, etc., and construct the magneto-optic inspection system.

Task 3 - construct test models including EDM (electro discharge machining) slots, inclusions, cracks in mild steel; obtain real flaws in the same materials. Model the effects of biofouling using nonmagnetic spacers (see Figure 8).

Task 4 - perform experiments on the test specimens, characterize the results and modify the magneto-optic inspection system, if necessary.

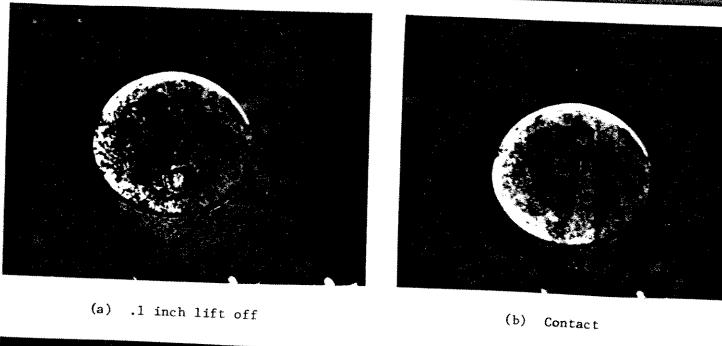Task 5 - prepare a final report and make recommendations for additional Phase II work at this time.

PHASE I ACCOMPLISHMENTS

System Design

Originally, we intended to employ front surface mirrors in an optical stack as shown in Figure 6. The principal reason for doing this was to exclude ambient light. This may yet be attempted (Phase II) since it could also result, because of multiple internal reflections, in a greatly enhanced image contrast. However, for the purposes of the Phase I feasibility demonstration, it was decided to keep the design as simple as possible and eliminate the front surface mirrors. We chose the simple design of Figure 9 for the optical arrangement. Note that a current-carrying coil (not shown) is assumed to surround this 'optical stack'.

Our first goal was to produce a simple prototype device having the general features of the final system. The device we produced is illustrated in Figure 10. It consists of a commercially available electroluminescent panel (aircraft green) measuring 1/16 inch thick by 3/4 inch wide by 2 inches in length, a garnet film (.02 inch thick) and two pieces of Polaroid (HN42) as shown in Figure 9. A small coil form surrounding this rectangular stack was constructed and 100 turns of # 32 copper wire was wound on the form. A circuit (similar to that in Figure 11) designed to drive the coil (see waveform in Figure 12) was then constructed, and the device illustrated in Figure 10 was assembled.

The current waveform (Figure 12) is designed to sensitize the crystal and to erase prior images. By choosing the duty cycle shown, it was also possible to operate the device on four AA size alkaline batteries (1.5V).

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(a)   .1 inch lift off

(b)   Contact

(c)   .25 inch lift off

(d)   Contact

Figure 8.   This figure illustrates images produced by two different targets at two lift off distances using a reflection-type imager (see Figure 3).   In (b) a permanently magnetized flat plate containing a two inch long inclusion is being inspected with the viewer contacting the surface.   In (a) the viewer is at a lift off distance of .1 inches.   Similarly in (d) we have a contact image taken on the outside of circumferentially magnetized pipe (OD 4 1/2 in., wall thickness 1/4 in.) containing a tight crack which extends through the wall.   In (c) this same crack, or rather the anomaly it produces, is viewed at a lift off of 1/4 in.   Clearly, the anomalies due to these flaws are still visible at considerable lift off distances.   This can be important, since marine fouling and/or surface irregularities may be present.   It should be noted that the images on (a) and (c) would be improved if instead of a statis field, we had applied a strong magnetizing field at the time of inspection.   The application of such fields during the inspection process can increase the distance the flaw can be seen through fouling.
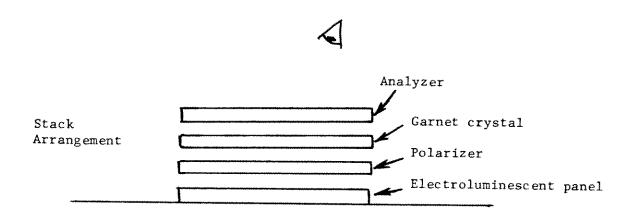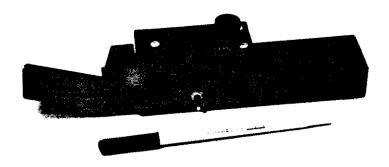
Figure 9.   The basic experimental arrangement.

Figure 10. Prototype Underwater Flaw Imager.

Power for both the electroluminescent panel (1000V DC) and the coil surrounding the optical stack was supplied by these cells.

Experiments with this device indicated that it worked very well. The intensity of the electroluminescent panel was sufficiently bright that images could be seen under most ambient light conditions (except direct sunlight). However, the electroluminescent panel was too thick to get good images of certain flaws. This is not a crucial concern where large (long) cracks are involved, but it was decided that thinner panels would be desirable. Moreover, the system was not watertight. Having demonstrated that a simple prototype worked we then set out to increase its size and make it watertight.
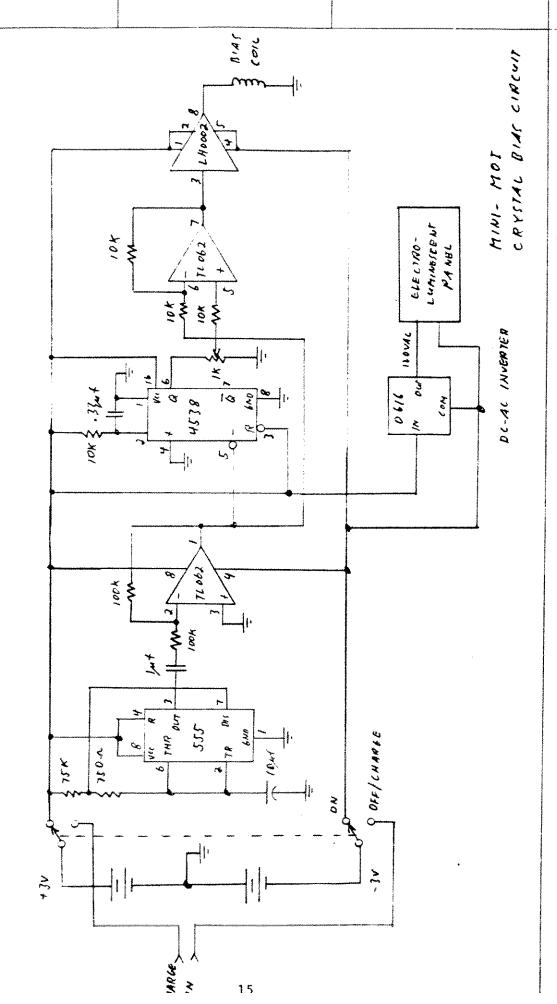
Scaling Up

The first step in this process was to obtain larger electroluminescent panels that were also thinner. Accordingly, we requested that the manufacturer produce panels of the type illustrated in Figure 13. These panels are waterproof and have a minimum thickness of .022 inches. Special coil forms and potting molds were then machined in preparation for constructing our first full-scale prototype underwater flaw imager.

The new device was designed to employ a full sized (three inch diameter) garnet film, using a coildrive circuit similar that depicted in Figure 11, and a stack of epoxy potted optical elements similar to those shown in Figure 9.

Tests were first performed to determine if the epoxy would attack the Polaroid, the electroluminescent panel, or the garnet film. The results were negative, suggesting that we could probably successfully put the optical system in a watertight configuration. However, there was some concern that the optical qualities of the epoxy (a water-clear epoxy), especially its potential for stress induced polarization, could be a problem. No data could be obtained on this material but our inspections of small cured samples did not show any polarizing effects, so we decided to proceed with this material. It was also noted that the epoxy was quite brittle. This could produce problems when pressure or temperature changes are rapid and will be discussed later. It might be necessary to go to a softer material exhibiting greater plasticity.

Construction

The second level prototype illustrated in Figure 14 was constructed in several stages. First a teflon mold was machined to produce a potted version of the optical stack. In order to remove all air bubbles from between the optical layers, the stack which was held in the mold was evacuated in a desiccator. Epoxy that had been poured between the optical elements and above the stack boiled under these conditions and, of course, all entrapped air was withdrawn from between these layers. After a period of about five to fifteen minutes, the air pressure in the chamber was slowly allowed to return to normal (duration about one minute). This gave the viscous epoxy time to fill voids. We quickly learned how to prepare optical stacks with very few entrapped bubbles or other defects.

Figure 11. The coil drive circuit.

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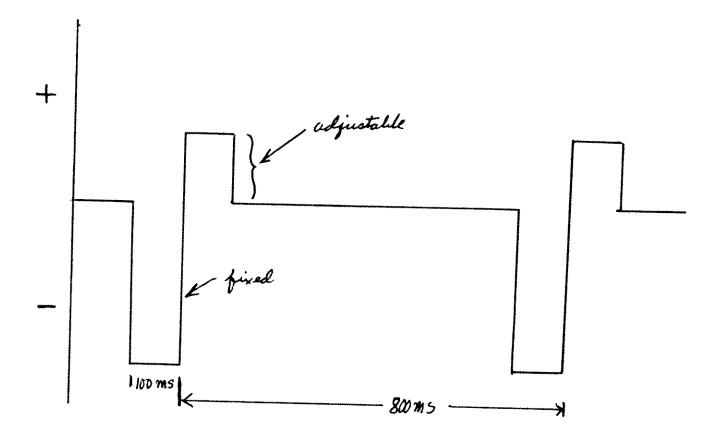
Figure 12. Relative current pulses supplied to the coil surrounding the garnet film.

Figure 13. Electroluminescent panels for planned full scale underwater flaw imager.

3.00" DIA ACTIVE AREA

3.25" DIA MX

.75"

LAMP THICKNESS .015" ±.005"

WITH PROTECTIVE COATING

TO PREPARE FOR EPOXY

BONDING ON BOTH SIDES

TOTAL THICKNESS .019" ±.005"

NUMBER REQUIRED:
AVIATION GREEN ~5
YELLOW GREEN ~3
BLUE GREEN ~2

SIGMA RESEARCH INC
8710 148th AVE NE
REDMOND WA 98052
(206) 881-1807

REF PO# 66773 14311

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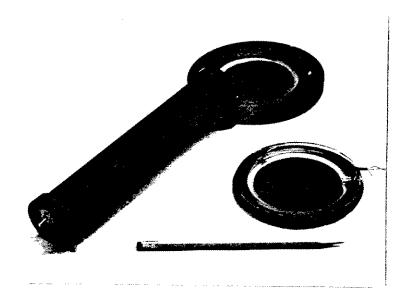Figure 14. The Phase II prototype imager. This is a hand-held, battery-operated device. The optical stack and surrounding coil are attached to a flashlight-like tube housing the circuits and batteries. An extra optical stack (plus coil) next to the imager is in the foreground.

However, it was often difficult to remove these potted stacks from the molds without either breaking the garnet crystal or shattering the epoxy. As mentioned earlier, the epoxy is of a very brittle sort that will probably have to be changed later. Due to these difficulties, some changes were made in the teflon molds and this led to a considerable reduction in the problem of cracking the epoxy.

The next step involved inserting this optical stack in a coil form, winding a 100 turn coil (#21 copper wire) measuring five inches in average diameter around the stack (3 1/4 inches in diameter), and inserting this combination in a second teflon mold for a second potting operation. This second operation, like the first involved removal of the air (in the coil) and in the spaces between the optical stack and coil form. Epoxy flowed into these void spaces as the pressure was slowly allowed to increase in the desiccator to one atmosphere.

At the completion of this second potting, the optical elements (plus coil form) represented a single watertight package (see Figure 14). A device looking somewhat like a lens holder was machined to hold the elements and provide connections to the electronic circuits housed inside a flashlight-like tube (Figure 14). Batteries (rechargeable AA nickle-cadmium or lithium chloride) were housed in this tube, and the tube was fitted with watertight seals (for shallow water operation). A watertight (for shallow operation) on-off switch was also provided in the unit. For deeper water operations, the watertight switch would have to be replaced by a small external magnet and something like a Hall-effect device inside the tube. This could be made into a switch that requires no mechanical connections to the tube interior. It will also be necessary to use O-rings to seal the tube. These items and problems will be discussed in more detail under the Phase II proposal.
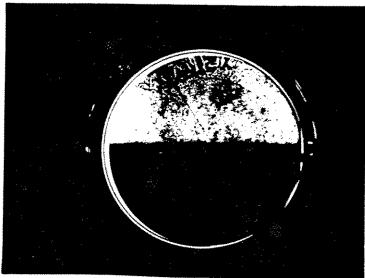
Performance

There are two competing aspects of the images produced by these devices, namely image intensity and image contrast. Unfortunately, the electroluminescent panels are not terribly bright light sources. Moreover, when the optical elements are potted in epoxy, there is a tendency to reduce the light that is transmitted through the system owing to multiple internal reflections.

If one adjusts the light intensity to be a maximum (by adjusting the polarizer) it happens that the contrast (intensity difference between a north pole and a south pole) in the image is greatly degraded or nonexistent. Conversely, if one adjusts the contrast to be a maximum, the intensity is greatly reduced. This can be compensated either by increasing the voltage to the electroluminescent panel (which shortens its lifetime) or by sacrificing contrast.
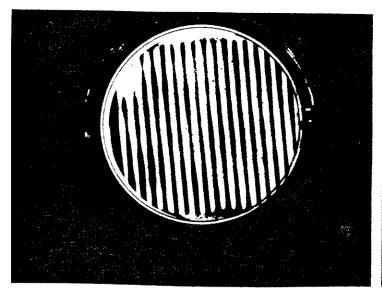
Experiments with the system suggest that contrast is important and that intensity (especially in an underwater environment where it is often dark) is less important. In any case there are good reasons for expecting that brightness can be improved by increasing voltage to the electroluminescent panel as mentioned above.
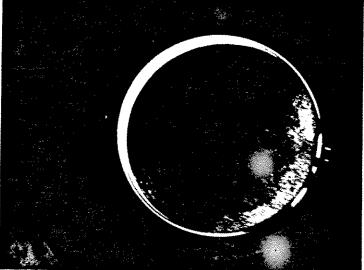
1/4 inch spacer

Contact

Barchart

Unflawed area

Figure 15. Images made using the device of Figure 14 and a long (9 ft.) pipe
            (4 in. OD, 3 3/4 in. ID) containing a longitudinal crack. Also
            shown for comparison is an image of a magnetic barchart.

In Figure 15, we illustrate an image of a long crack in a steel pipe (mild steel, four inch OD, 3.75 inch ID) as seen by the imager. This pipe specimen was magnetized by passing a 600 ampere (half wave rectified) current along the length of the pipe. The fields inside (and outside) the pipe are circumferential and leak out in the flaw area. The flaw shows up as a sharp discontinuity in the image. A nearby region (where there is no flaw) in the same figure is shown for comparison. The anomoly is still visible through a 1/4 inch spacer representing biofouling.

PHASE II TECHNICAL OBJECTIVES

The objectives of the Phase II program will be to fully assess the feasibility of developing an underwater flaw imaging system that meets the stated needs of the U. S. Coast Guard and other users. The Phase I prototype will be redesigned both to meet any user recommendations and to withstand the rigors of actual use in an underwater environment. The minimum objectives that must be met are:

1. Determine if the materials currently used (epoxys, plastics, etc.) will withstand the conditions of temperature and pressure expected. It is particularly important to determine if changes in temperature and pressure will affect the potted crystal. That is, will stresses cause cracking? It is also important to determine if the corrosive environment of seawater will be a problem for any of the proposed materials.

2. We must determine if the currently configured device is compatible with the anticipated needs of the user(s). It is recognized that such devices may be used in a number of different ways by a number of different users. Each application will require that the structural component be properly magnetized in order to insure that a flaw has been found. This is crucial if the flaw imager is to do its job. Therefore, we must work closely with the potential users [especially those such as J. P. Kenny (Appendix I) or the DOI Offshore Minerals Management] who would perform evaluations and provide recommendations on this new technology.

3. Transfer this technology to the user(s) in the forms most desirable to them. It is anticipated that the device may take different final forms for different applications. The shape of the viewing window can be altered in many cases to fit into special areas for special inspections. We are prepared to accommodate these needs by varying the window design as needed.

4. Determine what kinds of documentation best suits the user(s). In many cases the only requirement will be to find a crack and mark it with an appropriate indicator for later repair. In other cases, detailed photographic or other documentation will be needed. We will determine what is needed in each case.

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RELATIONSHIP WITH FUTURE RESEARCH AND DEVELOPMENT

The Phase I effort has demonstrated the feasibility of using magneto-optic imaging techniques to form flaw images in ferrous materials using a special sandwich optical design involving an electroluminescent panel, garnet film and other optical elements. This demonstration opens the way to further research and applications. Phase II will be directed toward more specific applications including particular problem areas defined jointly by the Coast Guard and Sigma Research.

It has also been brought to our attention that J. P. Kenny and Partners, Ltd. of the United Kingdom (see Appendix I) is very interested in this work. J. P. Kenny is currently acting as a research management for the SIM program (a consortium of oil companies and the U. S. Coast Guard). They have agreed to perform independent tests with the Phase I prototype and provide recommendations. We suggest that these tests could begin shortly after the Phase II program begins, and could provide valuable input and guidance to that program. However, we also suggest that Sigma provide guidance and any expertise needed in order to properly evaluate the Phase I prototype. It has been our experience that a proper knowledge of the technology is a prerequisite to its successful application. For this reason, we wish to participate in such tests (at least in an advisory capacity) on a funded basis (Phase II).

POTENTIAL APPLICATIONS

Owing to the anticipated capability of the proposed technology to provide a practical marine inspection tool, we anticipate that devices based on this new technology will be a commercial success. Accordingly, Sigma Research will make a Phase III commitment to develop a commercial product based on this research (see Phase III commitment). We will also seek additional outside Phase III funding support following the completion of the Phase I feasibility demonstrations.

PHASE III - FOLLOW-ON FUNDING COMMITMENT

Sigma Research fully intends to develop a commercially viable product from the theoretical and experimental results of Phase I and Phase II. We feel that a magneto-optic based device having the potential for marine inspection of flaws in ferrous materials such as mild steel would have great commercial significance. We base this projection first on our success at commercialization of our MI-201 ferrous metals inspection system (described in the proposal) which we now market and sell. Secondly, we observe that no device of the type proposed in Phase I exists for forming images in real time of surface and near surface flaws in ferrous materials in a marine environment where biofouling may be significant.

Discussion with Coast Guard representatives indicates that there exists a strong and continuing need to locate and/or monitor flaws in a range of structures including offshore platforms, ship hulls, drive shafts, etc.

If the Phase II effort succeeds as we anticipate, it will meet the following objectives:

1. Provide further proof of basic feasibility and clarify the optimum design parameters.

2. Demonstrate that sufficiently portable devices can be built to be useful in a marine environment.

Sigma Research has a strong commitment to product development and one of its corporate goals is to derive 50% of revenue from products by 1989. As a result, Sigma wishes to fund any resulting Phase III follow-on work on an internal basis. Therefore, if the above objectives are attained and the market potential remains attractive, Sigma Research will commit up to 580 man hours (approximately $50K) in addition to $10K for materials and equipment needed to develop a Phase III commercial prototype system. This support will be derived in part from our IR and D allocation and the balance financed by our credit bankers. We believe this level of effort will be adequate for Phase III based on our experience with the MI-201. A specific signed Phase III commitment will accompany the Phase II proposal.

PHASE II FUNDING

It is proposed that the total Phase II contract amount ($300,000) be divided between two government agencies namely the DOT (Coast Guard) and the DOI (Offshore Minerals Management). In a discussion at Sigma Research with Charles E. Smith (Research Program Manager - Offshore Minerals Management, Dept. of the Interior) he suggested that the $300,000 program could be supported jointly by DOI ($100,000) and by DOT ($200,000). He indicated in April of 1987 that he would discuss this possibility with appropriate DOT personnel.

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8. If the transmission coefficient of the FSM nearest the electroluminscent panel in Figure 6 is t_1 and that of the second FSM t_2, then the light transmission after one multiple reflection between these mirrors is proportional to $T = t_1(1-t_1) t_2(1-t_2)$. Holding t_1 fixed and setting $dT/dt_2 = 0$ we find that $t_2 = .5$ or 50% transmission is required to maximize T. But this means that t_1 is also 50% by the same reasoning. Combining these transmission factors, the effects of the FSM's if $t_1 = t_2 = .5$ is that only about 7% of the light escapes to the viewer. Thus, we may have to increase t_1 and t_2 to get more light and somewhat lower contrast.